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Modeling and Performance Analysis of a new PVT system, With Two Semi-Transparent PV Panels

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Abstract

Photovoltaic-thermal collector (PVT) system is a relatively mature technology to harvest energy from the sun and convert to electrical and thermal energy. Recent developments in this field have shown that the PVT system can yield electrical, thermal and combined PVT efficiencies of 13.8%, 54.6% and 68.4% respectively. This introduces the application of a semi- transparent PV to a photovoltaic thermal collector (PVT) system. A new design is proposed with two semi-transparent PV (STPV) to enhance the PVT performance. The semi-transparent (STPV) will replace the conventional glass cover, hence; will permit a certain percentage of solar radiation to pass through it. The performance of the new PVT configuration with double and single glazing was analysed. Where in the double-glazing, the STPV to replace the lower glazing. The thermal and electrical efficiencies of the new design configuration were investigated under different climatic conditions at Malaysia, Sudan and United Kingdom. The simulation results reveal that, the new PVT system could achieve electrical, thermal and combined PVT efficiencies of 20.76 %, 65.7 % and 86.5 % respectively. Enhancing the electrical efficiency due to the use of two semi-transparent PV panels. Thus improving the energy harvested per unit area, putting positive step towards the application of a multilayer semi-transparent mono crystalline silicon PV. However, the PVT glazing is more effective in locations with relatively low ambient temperature. While it is found not feasible in locations with considerable higher temperature. Moreover, the study indicates that, PVT system is not effective for sites with low solar radiation and ambient temperature.

1. Introduction

Solar energy is regarded as the most abundant energy source. It is considered as a clean energy spread all over the earth unlike other sources of energy that are site restricted. Over the years, fossil fuel has been the dominant source of energy, but recent environmental pollution issue has raised the concern over the continuous use of fossil fuel. Therefore, the need to harness renewable energy resource is becoming increasingly high, as highlighted by (Bijarniya, Sudhakar et al. 2016).

Solar energy is harvested with photovoltaic (PV) to generate electricity while solar thermal collectors are used to harvest heat energy. Recent developments provide a more efficient way of harnessing both thermal and electrical energy with the introduction of Photovoltaic thermal system (PVT). The PVT system is a combined unit to extract electricity and heat simultaneously from the sun, (Fudholi, Sopian et al. 2014).

The conventional PVT, consists of a PV panel and a flat plate collector, they are either glazed or unglazed. Flat plate collector type has a huge potential for low temperature heating application. The PV panel will be placed on the absorber plate of the collector to cool the PV panel by conveying heat energy to the water circulated through the absorber (Zondag 2008, Teo, Lee et al. 2012). Many researches indicate that, there is a greater potential for the use of PVT system. The combination of PV panel and flat plate collector leads to increase in both thermal and electrical efficiency of the system (Kalogirou 2014, Kumar, Baredar et al. 2015).

This work intends to introduce the application of a new configuration PVT, provided with two semi-transparent PV (STPV). The STPV allows a certain percentage of solar radiation to pass through; hence, it is used to replace the glass cover of the collector. While the second STPV (STPV2) is placed on the absorber plate and cooled by the circulating fluid through the absorber. In this new PVT, it is expected to improve the combined efficiency and would make the system more robust, through the enhancement of the system performance and improve the electrical energy harvested per unit area. There is a very limited research work on STPV panels. Therefore, the novelty of this work is to replace the glass cover with a STPV. Moreover, will open the chances for STPV multilayer application. Figure 1 illustrates the conventional PVT and the new PVT with the 1st semi-transparent PV (STPV1) replaced the glass cover, while the 2nd Semi-transparent PV (STPV2) replaced the normal PV panel.

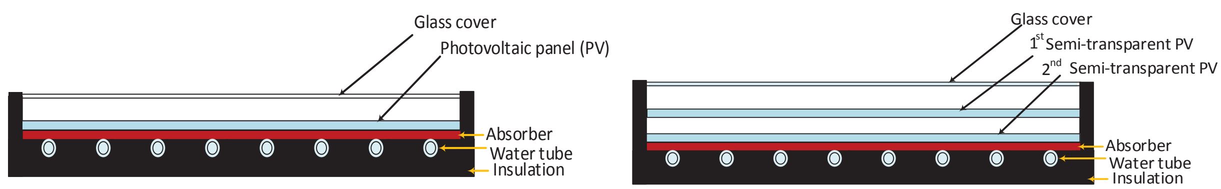

Fig.1: illustrates the conventional PVT and the new PVT with STPV replaced the glass cover (Visio 2010)

A mathematical model is developed to investigate the thermal and electrical efficiencies of the new PVT configuration compared to the performance of conventional PVT system under different climate conditions. The study is performed using the climate conditions of three cities with high, medium and low solar radiation and ambient temperature for the cities Khartoum, Kuala Lumpur and Edinburgh respectively.

Photovoltaic thermal (PVT) collector is a module that combines both photovoltaic and solar thermal collector to produce electrical and thermal energy simultaneously. It is composed of glazing on top, PV panel, absorber plate and insulation material (Greene and Heaney 2007, Tyagi, Kaushik et al. 2012). A photovoltaic (PV) cell produces electricity using a fraction of the incident solar radiation received. Some of this energy is turned into waste heat, which causes the temperature of PV to rise. Increase in temperature significantly reduces the efficiency of PV cells (Ferguson and Fraas 1995, Salmi, Bouzguenda et al. 2012). Therefore, by introducing a solar thermal collector to the PV configuration the system temperature could be reduced while the recover this waste heat. This acts to reduce the cell temperature while improving the overall efficiency (Fraisse, Ménézo et al. 2007, Fudholi, Sopian et al. 2014). The PVT collector could produces 20% to 40% more energy per square meter than a separate PV panels and solar thermal collectors (Calise, d'Accadia et al. 2012, Buonomano, Calise et al. 2013). The common PVT collector types use the water or air to harvest the thermal energy, they are either glazed or unglazed (Chow 2010).

Solar PV panel is a main component of the PVT system, where it absorbs some of the sun light, and some amount is reflected. The top glass layer is an important components of a solar panel, it reflects only a portion 3-4% of the sun light (Gong, Darling et al. 2015). Semi-transparent PV panel on the other hand is designed to behave like glass by allowing a certain amount of solar radiation to pass through, while generating electricity. A solar PV that is 50% opaque allows about 50% of solar radiation to pass through it, hence, it is suitable for integration into building or other applications in need for light transmittance (Saifullah, Gwak et al. 2016).

Garg and Agarwal developed a simulation model to analyse the PVT performance, it was observed that the system performance was largely dependent on the ambient temperature. It is also concluded that, an additional cover will significantly reduce heat transmission losses and will increase the system temperature compare to single cover. Thus, causing the system with double glass cover more potential of receiving more heat compare to single cover glass cover (Garg and Agarwal 1995). In their experiment examined the performance of the PVT system with single and double glass using a steady state model. It was noted that, the PVT with double pass using normal operational mass flow rate was considerably better compare to the single pass PVT. However, this is subject to location as single glass cover is good for location with high ambient while double glass cover is suitable for location with low ambient temperature (Sopian, Yigit et al. 1996, Ibrahim, Othman et al. 2011) .

Similarly, Fraisse et al (2007) tested the PVT performance, the mono crystalline PV was considered due to its low temperature operating condition. The result recorded a 2.6% drop in annual efficiency of a PV panel due to the increase of the cell temperature, since the cover increase the cells temperature. For a similar system with no cover, the electrical efficiency was recorded to be 10%, which is 6% better when compared to the standard PV module due to the cooling effect of the system by the flowing fluid. They concluded that, the PVT design must be determine with respect to the ambient temperature (Fraisse, Ménézo et al. 2007).

Adnan et al (2015) conducted an experiment with single glazed flat plate PVT collector, the simulations result shows that, the system with spiral flow design achieves high performance with the PVT system achieving thermal, electrical and combined efficiency of 60.12%, 11.98% and 71.14% respectively (Ibrahim, Othman et al. 2009, Ibrahim, Fudholi et al. 2014).

Michael et al. (2015) conducted a review on different types of PVT including glaze and unglazed PVT; the results is presented in Table 1. It was found that the PVT system leads to 8% increase in electrical energy compared to the stand-alone PV module due to cooling provided by the flowing fluid. The glazed PVT system produces more thermal energy than the unglazed and due to heat trap in the system because of the cover. Finally, it was found that the total energy from the covered PVT was 11% more than the uncovered system and the combined efficiency of the PVT system ranges between 65% to 76% depending on the system design and climate conditions (Michael, Iniyan et al. 2015).

Table 1 Summary of PVT Efficiency(Michael, Iniyan et al. 2015).

PVT type	Thermal efficiency	Electrical efficiency	Combined efficiency	Reference
PVT water system	64%	12%	76%	(Dupeyrat, Ménézo et al. 2011)
PVT with opaque PV	60.5%	9%	69.5%	(Daghigh, Ruslan et al. 2011)
PVT single pass	64.5%	11%	75.5%	(Bai, Chow et al. 2012)
PVT spiral flow	64%	11%	75%	(Fadhel, Sultan et al. 2013)
PVT single glaze	58%	8.9%	66.9%	(Sultan, Fadhel et al. 2013)
PVT double glaze	60%	8%	68%	(KADHIM, YAZDI et al. 2013)

In an experiment conducted by Kadhim et al (2014) under Malaysia climate conditions, it was concluded that the PV cells generate more electricity with increase solar radiation and the cell efficiency reduces due to increase in ambient temperature. For that experiment, the PVT system achieves electrical efficiency of 11.5% and thermal of 65.8%, making the PVT to achieve combined efficiency of 78.3% (KADHIM, YAZDI et al. 2013). For high thermal efficiency, the gross/aperture area ratio, optical efficiency, heat removal factor and thermal insulation must be maintained similar to solar thermal collector (Fortuin, Hermann et al. 2014).

Erdil, IIkanet al. (2008) examined hybrid PV solar thermal system in Northern Cyprus, the experiment considers a typical household to consume an electrical energy of about 7 kWh daily and require a PV covering about 10 m^2 area to produce such electrical energy. However, they made use of two PV modules covering an area of 0.6 m^2 each. They concluded that the PV module absorbs much heat from the solar radiation, which can be used for water pre-heating. It was also observed that about 2.8kWh thermal energy was produced daily (Erdil, Ilkan et al. 2008).

Dubey and Tiwari (2009) performed analysis of the PVT collector using flat plate collector that are partially covered. The system was connected to a DC motor, which is powered by the PV module and used to circulate water in the collector. They performed different evaluations and the system was proven economically viable. From the economic analysis, it was concluded that the system if installed in about 10% of household in Delhi India would significantly reduce the cost of electricity. (Dubey and Tiwari 2009).

2. Methodology

This analysis uses a PVT system with design parameters similar to the system used in the performance analysis of PVT water collector (Fudholi, Sopian et al. 2014), which will referred in this study as the typical PVT. The hourly climate condition for this research was obtained between 8:00am to 18:00pm from meteorological forecast of the [1]Meteonom© and [2]PVsyst© for three locations with high, medium and low solar radiation and ambient temperature. The locations details are given in Table 2.

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[1] Meteonorm© 7.1: Irradiation data for every place on Earth
[2] PVsyst©: Software for photovoltaic systems

Table 2 Locations considered for this analysis

Country	Location	Latitude	Longitude
Sudan	Khartoum	N15.60	E32.55
Malaysia	Kuala Lumpur	N3.12	E101.55
United Kingdom	Edinburgh	N55.60	W-3.19

Fig. and Fig. 3 illustrate the annual mean daily solar radiation and ambient temperature at the respective locations

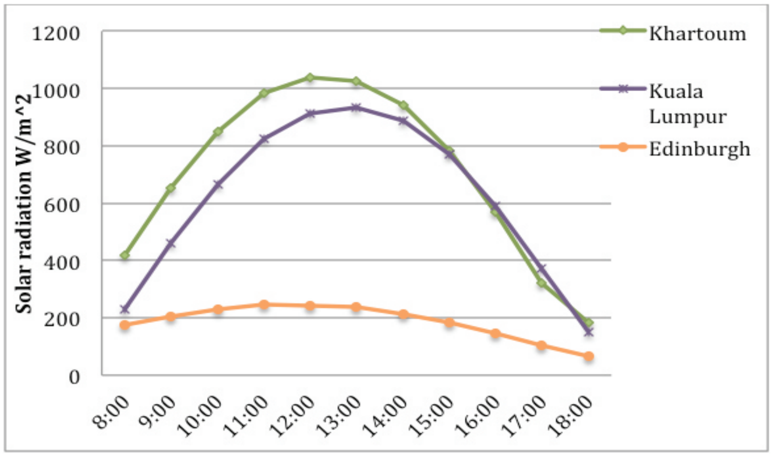


Fig. 2 Solar radiations for Khartoum, Kuala Lumpur and Edinburgh

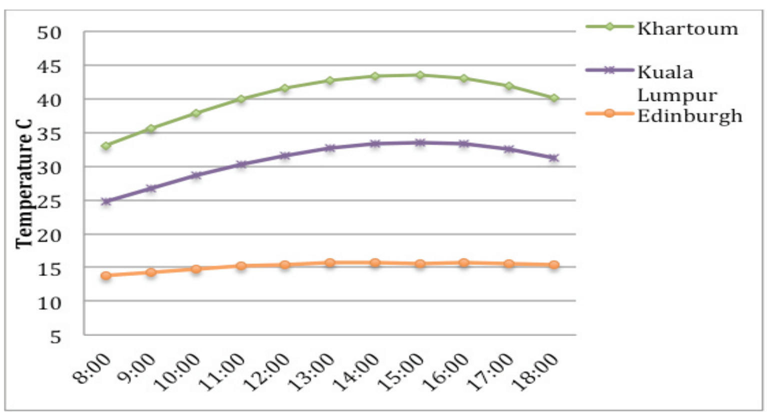


Fig. 3 Hourly temperatures for Khartoum, Kuala Lumpur and Edinburgh

The above data represent a typical sunny day with a clear sky solar radiation and ambient temperature ranges between 158-1045W/m^2 and 33-43.5 respectively for Khartoum. Similarly, Kuala Lumpur has solar radiation and ambient temperature between 152-935W/m^2 and 23-35^{o}C respectively. For Edinburgh the solar radiation and ambient temperature between 66-246.9W/m^2 and 13-17^{o}C respectively (Simo-Tagne and Bennamoun 2018), Meteonorm Software (2016).

The methodology used for this work include the thermal analysis and the system performance, which includes the useful energy, electrical, thermal and overall or combined PVT efficiency. A flow chart for the processes applied to both PVT with glass cover and without glass cover under different weather conditions to enables a better prediction of the system design suitable to locations according to climate condition.

2.1. Thermal analysis of PVT collector system

There are three-dimensional losses in the PVT collector, which occurs at the top (Top losses) from the absorber plate to the cover, the losses at the backside (back losses) occurs from the absorber plate through the back insulation and the final loss occurs in the edge (Edge losses). The losses are add up together and considered as the overall losses coefficient of a solar flat plate collector (Duffie and Beckman 2013),

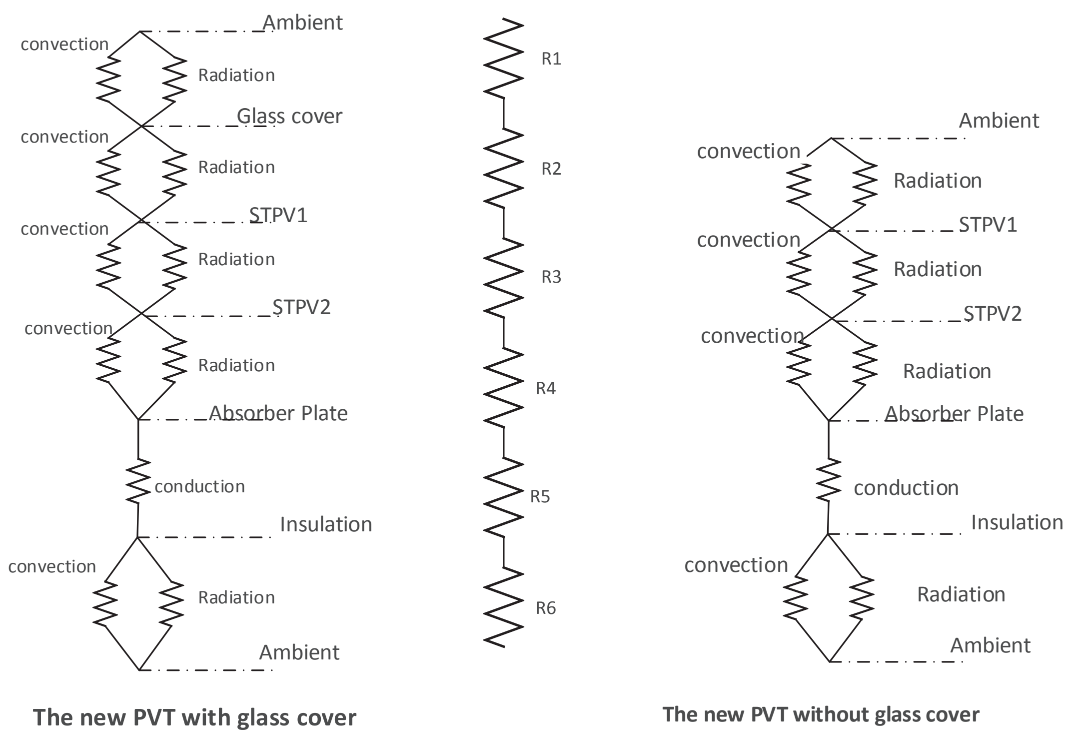


Fig. 4 Thermal resistance circuit for the new PVT provided with two semi-transparent PV (i.e. STPV1 and STPV2) (Visio 2010)

The top energy losses are due to convection and radiation between parallel plates. The steady-state energy transfer from the absorber plate to the second semi-transparent PV (STPV2) by convection and radiation, represented by the thermal resistance R4 and from the STPV2 to the STPV1 represented by R3. While the same heat transferred from the SPTV1 to the glass cover represented by R2 and from the glass cover the energy lost to the surroundings represented by R1 Therefore, the heat transfer from the absorber plate to the topmost cover can be expressed as the sum of energy loss per unit area through the top. Figure 4 illustrates the thermal resistance circuit for the new PVT provided with two STPV. Table 3 shows the PVT design parameters used for this analysis, which is similar to the typical PVT (Fudholi, Sopian et al. 2014)

Table 3: The new PVT system parameters

Description	Value ,Unit
Total length of collector	1.173m
Total width of collector	0.65m
Aperture area	0.76245m^2
Length of absorber plate	1.123m
Width of absorber plate	0.6m
Absorber plate area	0.6738m^2
Plate to cover spacing	0.025m
Number of cover	1,2,3
Plate absorptivity / emissivity	0.95
Outer diameter of tube	0.025m
Inner diameter of tube	0.022m
Tube center to center distance (W)	0.02m
Back insulation thickness	0.05
PV absorptivity /emissivity	0.8
Glass cover emissivity	0.88
Glass cover absorptance	0.95
Thermal conductivity of plate material	385 W/mK
Plate thickness	0.002m
Heat transfer inside the water tube	333 W/mK
Water flow rate	0.045 kg/s
fluid thermal conductivity	0.613 W/mK
Absorber thermal conductivity	51 W/mK
Water specific heat Cp	4180 J/kg.K
Kδc (Glass cover extinction coefficient factor multiplied by cover thickness)	0.05
Refractive index of glass relative to air	1.526
Insulation thermal conductivity	0.045

Figure 5 illustrates the PVT thermal losses. The equations to evaluate the losses especially the top loss coefficient involves a nonlinear process and differential equations, therefore requires iterative solution. This analysis is performed under steady state condition using Microsoft excel.

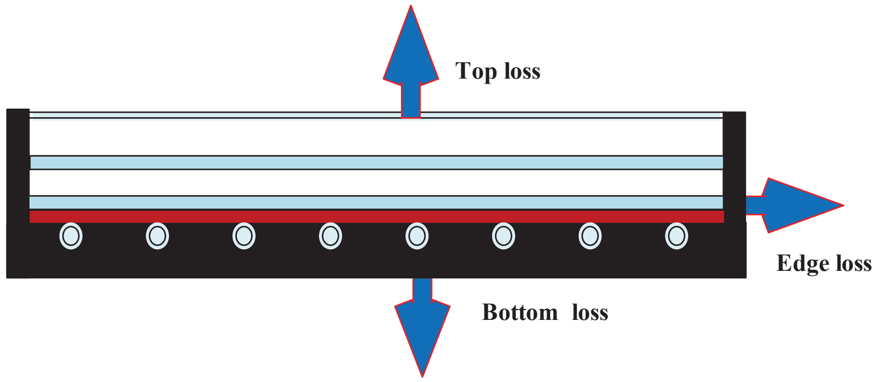


Fig. 5 illustrates the PVT thermal losses (Visio 2010)

The radiation and convection heat transfer evaluation was derived using the method suggested by Duffie and Beckman and is used to find the top loss heat transfer coefficient and cover temperature (Duffie and Beckman 2013) .

$$q_{loss,top} = h_{c.p-P_{v2}}(T_p - T_{pv2}) + \frac{\sigma\left(T_p^4 - T_{pv2}^4\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_{pv2}} - 1} \quad (1)$$

Where, $h_{c.p-pv2}$ is the convection heat transfer coefficient between the absorber plate and the semi-transparent STPV2. Where T_p is the absorber plate temperature and T_{pv2} is the STPV2 surface temperature

$$q_{loss,top} = h_{c.p-pv2} + h_{r.p-pv2}\,(T_p - T_{pv2}) \quad (2)$$

and

$$h_{r.p-pv2} = \frac{\sigma(T_p - T_{pv2})\left(T_p^2 - T_{pv2}^2\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_{pv2}} - 1} \quad (3)$$

Where, $h_{r.p-P_{v2}}$ is the radiation heat transfer coefficient between parallel plate i.e absorber plate and semi-transparent STPV2.

To find the convection heat transfer, we need the Nusselt, Rayleigh, and Prandtl numbers, which are given in the following equations (Duffie and Beckman 2013).

$$Nu = \frac{hL}{k} \quad (4)$$

$$Ra = \frac{g\beta'\Delta T L^3}{va} \quad (5)$$

$$\mathrm{Pr} = \frac{v}{a} \quad (6)$$

Where, h is the heat transfer coefficient (W/m^2 K). L is the plate spacing (m), k is the thermal conductivity (W/m K), g is the gravitational constant (m/s^2), β is the volumetric coefficient of expansion (for an ideal gas, β = 1/T), Tis the temperature difference between plates (K), ν is the kinematic viscosity of air (m^2/s), α is the thermal diffusivity of air m^2/s).

But for parallel plate Nusselt number is express by(Duffie and Beckman 2013).

$$\mathrm{Nu} = 1 + 1.44\left[1 - \frac{1708(\sin 1.8\beta)^{1.6}}{Ra\cos\beta}\right]\left[1 - \frac{1708}{Ra\cos\beta}\right]^{+} + \left[\left(\frac{Ra\cos\beta}{5830}\right)^{1/3} - 1\right] \tag{7}$$

The thermal resistance at this level (between the absorber plate and the STPV2) is as follows:

$$R4 = \frac{1}{h_{c.p-pv2} + h_{r.p-pv2}} \tag{8}$$

Where; $h_{c.p-pv2}$ and $h_{r.p-pv2}$ are the heat transfer coefficients between the absorber plate and the STPV2 for convection and radiation respectively.

The overall heat transfer coefficient at that level is represented as Ut_{pv2} and is given as

$$Ut_{pv2} = \left(\frac{1}{h_{c,p-PV2} + h_{r,p-PV2}}\right)^{-1} \tag{9}$$

Similarly, the same step is applicable to R3, R2 and R1, which are, represent the heat transfer coefficient by convection and radiation for the semi-transparent STPV2-STPV1, STPV1-glass cover and glass cover to ambient respectively. Hence, the corresponding thermal resistances and heat transfer coefficients are as follows:

$$R3 = \frac{1}{h_{c.pv2-pv1} + h_{r.pv2-pv1}}$$

$$Ut_{pv1} = \left(\frac{1}{h_{c.pv2-pv1} + h_{r.pv2-pv1}}\right)^{-1}$$

$$R2 = \frac{1}{h_{c.pv1-cover} + h_{r.pv1-cover}}$$

$$Ut_{pv1} = \left(\frac{1}{h_{c.pv1-cover} + h_{r.pv1-cover}}\right)^{-1}$$

The heat transfer coefficient from the top glass cover at a temperature T_c, to the surrounding has a similar equation. However, the convection heat transfers coefficient h_w is due to wind and the radiation heat transfer $h_{r,c-a}$ from top is as a result of radiation exchange with the sky temperature T_{sky}. Hence the top glass cover radiation heat transfer is given as (Santbergen, Rindt et al. 2010, Duffie and Beckman 2013).

$$h_{r.c-a} = \frac{\sigma \varepsilon_c (T_c + T_{sky})(T_c^2 + T_{sky}^2)(T_c - T_{sky})}{T_c - T_a} \tag{10}$$

The sky temperature T_{sky} in terms of the ambient temperature T_a is given by the following equation (Zondag H. A. 2008).

$$T_{sky} = 0.055 T_a^{1.5} \tag{11}$$

The convection heat transfer coefficient h_w is due to wind from the cover to the ambient at a temperature T_a is due wind convection coefficient given by Watmuff as (Watmuff, Charters et al. 1977, Duffie and Beckman 2013).

$$h_w = 2.8 + 3.0V \tag{12}$$

Where V is the wind speed in m/s and h is in W/m^2 K.Therefore the heat loss from the glass the cover to surrounding is given as

$$R1 = \frac{1}{h_w + h_{r.C-a}}$$

$$Ut_{c-a} = \left(\frac{1}{h_w + h_{r.C-a}}\right)^{-1}$$

Then the overall top loss coefficient U_t is given by the summation of all the losses at different layers from the absorber plate through the two semi-transparent PV to the top glass cover (Duffie and Beckman 2013). Hence, the top losses U_t for PVT system with and without glass cover are as follows:

Then the top losses U_t for the PVT with glass cover.

$$U_t = \frac{1}{R1 + R2 + R3 + R4} \tag{13}$$

$$Ut = \left(\frac{1}{h_{c,p-PV2} + h_{r,p-PV2}} + \frac{1}{h_{c,PV2-PV1} + h_{r,PV2-PV1}} + \frac{1}{h_{c,PV1-C} + h_{r,PV1-C}} + \frac{1}{h_w + h_{r,C-a}}\right)^{-1} \tag{14}$$

The top losses U_t for the PVT without glass cover;

$$U_t = \frac{1}{R1 + R2 + R3}$$

$$Ut = \left(\frac{1}{h_{c,p-PV2} + h_{r,p-PV2}} + \frac{1}{h_{c,PV2-PV1} + h_{r,PV2-PV1}} + \frac{1}{h_w + h_{r,pv1-a}}\right)^{-1}$$

The top cover temperature T_{cover} is expressed with reference to the plate temperature T_p and the ambient temperature T_a is represented as follows for the semi-transparent PV (STPV2), semi-transparent PV1 and glass cover respectively (Duffie and Beckman 2013).

$$T_{PV2} = T_P - \frac{Ut1(T_P - T_a)}{h_{c,p-PV2} + h_{r,p-PV2}}$$

$$T_{PV1} = T_{PV2} - \frac{Ut2(T_{PV2} - T_a)}{h_{c,p-PV1} + h_{r,p-PV1}}$$

$$T_{cover} = T_{PV1} - \frac{Ut1(T_P - T_a)}{h_w + h_{r,p-cover}}$$

The bottom loss is due to two series resistances R5 and R6. The R5 represents the conduction heat flow from the insulation material as given by equation (15). While R6 represents the convection and radiation resistance to the environment from the bottom side and is considered negligible

$$U_b = \frac{1}{R_5} = \frac{k}{L} \tag{15}$$

Where; K and L are the insulation thermal conductivity and thickness respectively.

The edge loss of the PVT system can be derived with reference to the collector area, assuming one-dimensional sideways heat flow around the collector perimeter. The edge loss is given as (Anderson, Duke et al. 2009, Tyagi, Kaushik et al. 2012, Duffie and Beckman 2013).

$$U_e = \frac{(UA)_{edge}}{A_c} \tag{16}$$

The overall loss for PVT is given by the summation of all the losses from the top, bottom and edge (Anderson, Duke et al. 2009, Duffie and Beckman 2013).

$$U_L = U_t + U_b + U_e \tag{17}$$

2.2. Performance analysis of the new PVT collector

The performance of the PVT includes the thermal and electrical analysis. The performance is affected by the design parameters, local climate condition and the water flow rate. The performance is evaluated using the Hottel-Whillier equation (Hottel 1958, Duffie and Beckman 2013).The PVT efficiency is the ratio of useful energy gained to the incident solar radiation on the PVT collector surface over a period of time. The sum of the electrical and thermal energy gain is known as overall or combined PVT efficiency and is given as (Fraisse, Ménézo et al. 2007, Dupeyrat, Ménézo et al. 2014, Fudholi, Sopian et al. 2014).

$$\eta_{PVT} = \eta_{pv} + \eta_{th} \tag{18}$$

The thermal efficiency (η_{th}) of a typical solar collector is as follows (Duffie and Beckman 2013, Dupeyrat, Ménézo et al. 2014).

$$\eta_{th} = \frac{Q_u}{G} \tag{19}$$

Where Q_u is useful heat gain (W/m^2) and G is solar-radiation receive by the collector (W/m^2). Hence, to evaluate the thermal efficiency, it is necessary to obtain the useful energy gain Q_u, which is given by (Duffie and Beckman 2013).

$$Q_u = \dot{m}C_p(T_o - T_i) \tag{20}$$

Where $\dot{m}$ is mass flow rate (kg/s), C_p is the specific heat of the cooling medium circulated through the collector (J/kg K), T_o is temperature of outlet fluid (K) and Ti is inlet fluid temperature (K).

The useful energy gain Q_u of PVT is given by Hottel-Whillier equations and is express as (Anderson, Duke et al. 2009, Duffie and Beckman 2013, Dupeyrat, Ménézo et al. 2014).

$$Q_u = A_c F_R[S(\tau\alpha) - U_L(T_i - T_a)] \tag{21}$$

Q_u is the useful energy gain, A_c is the collector area, F_R is the heat removal factor, S is the incident solar radiation, τ is the transmissivity, α is the absorbance, U_L is the overall thermal losses, T_i is the fluid inlet temperature, T_a ambient temperature

The incident solar radiation is affected by reflection, transmission and absorption; Hence S is given by(Duffie and Beckman 2013, Sancho Balsells 2014).

$$S = (\tau\alpha)G_T \tag{22}$$

Where, ($\tau\alpha$) is the transmittance and absorbance of the PV and G_T is the solar radiation. This represent a system with just a single PV layer, But for a double layer transparent PV system with semi-transparent properties, the surface is considered opaque, hence $\tau\alpha_{PV}$ is given by (Duffie and Beckman 2013).

$$(\tau\alpha)_{PV} = (\tau\alpha) + (1 - \tau_{\alpha})\frac{U_t}{U_{c-a}} \tag{23}$$

From the equation (21), it can observe that another important factor to determine the thermal efficiency and useful energy gain is the heat removal efficiency factor F_R which is expressed as (Duffie and Beckman 2013).

$$F_R = \frac{\dot{m}C_p}{A_c U_L}\left[1 - \exp\left(-\frac{A_c U_L F'}{\dot{m}C_p}\right)\right] \quad (24)$$

Where, *F'* is the collector efficiency factor and can be obtained by the following equation (Duffie and Beckman 2013).

$$F' = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L[D+(W-D)F]} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}}\right]} \quad (25)$$

Where D is the hydraulic diameter of the water tube (m),

W is the water tube spacing (m),

F is the fin efficiency factor,

C_b is the Conductance of the bond between the fin and water tube (W/m^{2}K)

h_{fi} is the Heat transfer coefficient of fluid (W/m^{2}K).

Also, to find the efficiency factor, the **Fin efficiency factor** is given as (Duffie and Beckman 2013).

$$F = \frac{\tanh\left[\frac{m(W-D)}{2}\right]}{\frac{m(W-D)}{2}} \quad (26)$$

Where, m is given by (Hasan and Sumathy 2010, Duffie and Beckman 2013).

$$m = \sqrt{\frac{U_L}{(k_{abs}L_{abs}) * (k_{pv}L_{pv})}} \quad (27)$$

Where k = absorber material thermal conductivity (W/m^2 K),

L_{abs}= absorber thickness (m),

k_{pv}= photovoltaic thermal conductivity (W/m^2 K)

L_{pv}= PV collector thickness.

The thermal efficiency of the PVT collector is calculated as (Hasan and Sumathy 2010, Duffie and Beckman 2013).

$$n_{th} = F_R(\tau\alpha)_{PV} - F_R U_L \frac{T_i - T_a}{G_T} \quad (28)$$

The electrical efficiency is calculated as follows (Calise, d'Accadia et al. 2012, Buonomano, Calise et al. 2013, Fudholi, Sopian et al. 2014).

$$n_e = n_{ref}[1 - \beta(T_{cell} - T_{ref})] \quad (29)$$

Where η_e is the electrical efficiency, n_{ref} is the semi-transparent PV (STPV) module reference efficiency (η_{ref}= 0.12), β is the temperature coefficient, T_{cell} = solar cell temperature (K), T_{ref}= reference temperature.

The T_{pm} mean plate temperature is used to replace the initial guess temperature (Duffie and Beckman 2013).

$$T_{pm} = T_{fi} + \frac{Q_u/A_c}{F_R U_L}(1 - F_R) \tag{30}$$

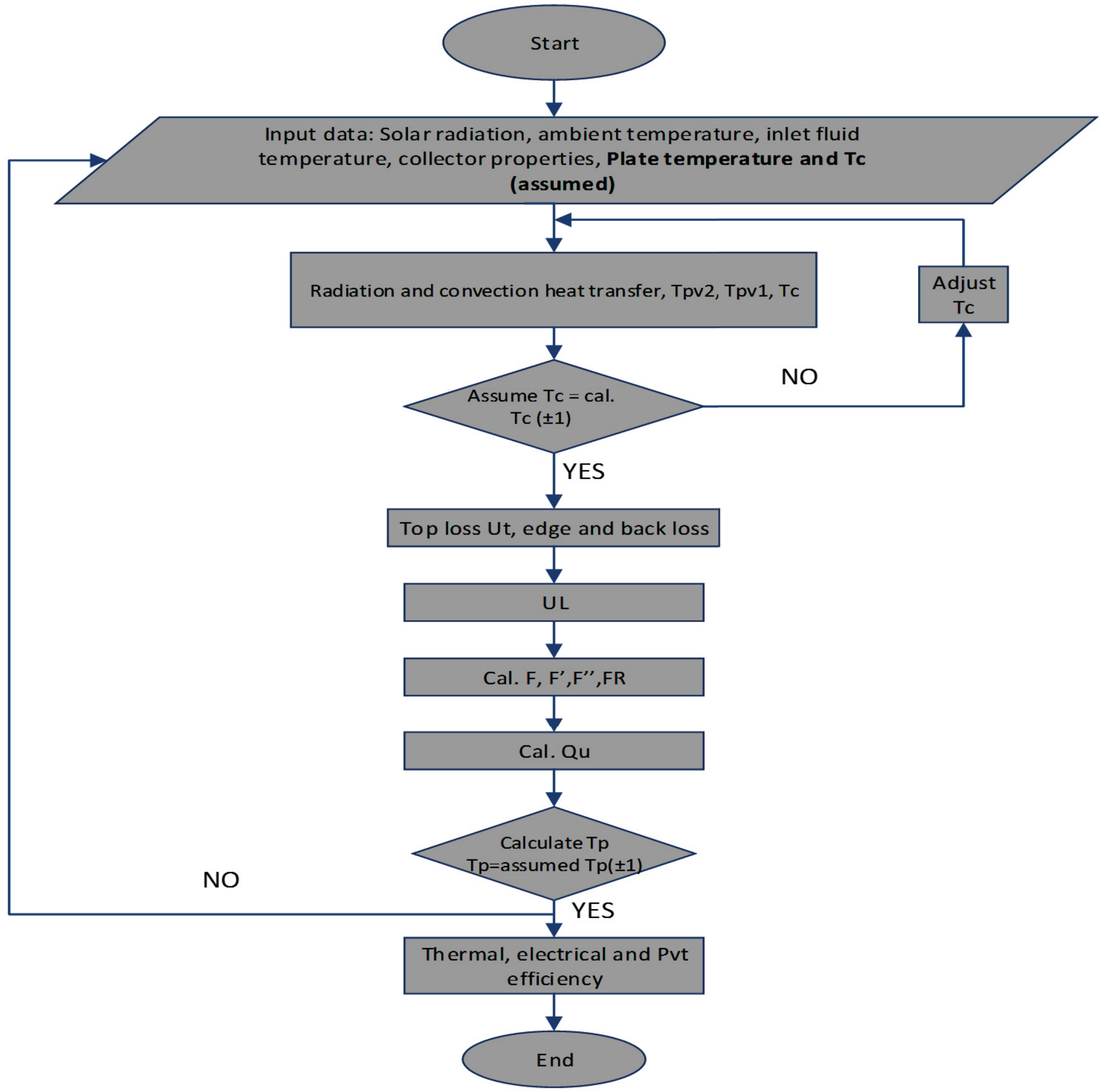


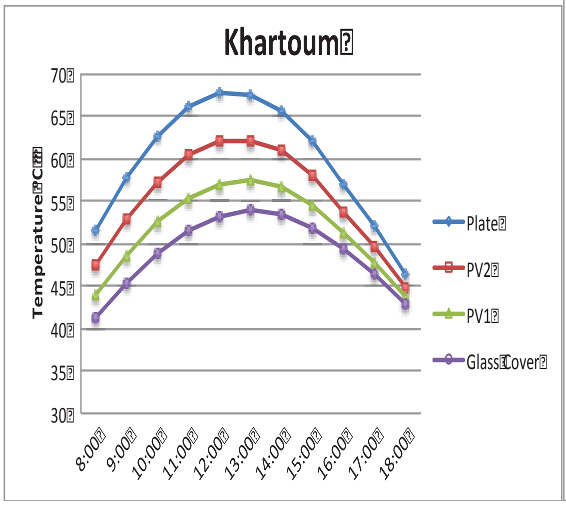
Fig. 6 illustrates the flow chart for the thermal and performance analysis of the PVT.

Figure 6 illustrates the thermal and performance analysis of the PVT. Initially, the mean plate temperature and the cover temperature are assumed, and used to estimate the convection and radiation heat transfer and subsequent cover temperatures. Through an iterative solution, the new cover temperature must be equal to the initial assumed cover temperature (Tc =± new Tc), is repeated until the condition is satisfied. The Top (U_T), back (U_B), edge losses (U_E) and subsequent overall loss (U_L) are calculated. Then the useful energy is calculated and used to calculate for the new mean plate temperature T_p. The new T_p must be equal to the initial assumed Tp (Tp =± new Tp), else a new initial Tp is assumed and the process is repeated until the condition is satisfied. Ones the condition is satisfied, the useful energy is use to derive the thermal, electrical and combined PVT efficiency.

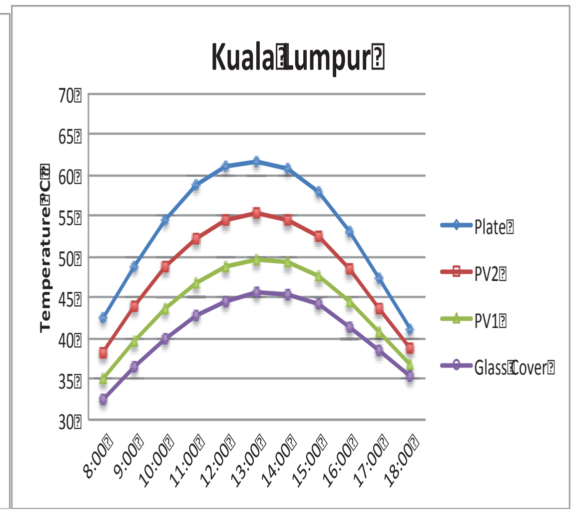
3. Results and Discussion

The performance of the new PVT collector is a measure of its electrical, thermal and combined efficiencies. Hence, the results discussion will focus on the different layer temperature of the new PVT, useful energy, electrical and combined PVT efficiency.

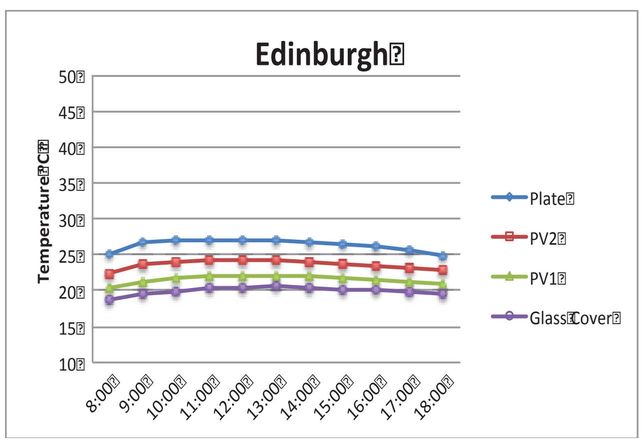
3.1. The different layers temperature of the new PVT



(a)



(b)



(c)

Fig. 7 the different layers temperatures across the new PVT in Khartoum, Kuala Lumpur and Edinburgh respectively

Fig. illustrates the temperatures of the glass cover, PV1 for STPV1, PV2 for STPV2 and Plate for the absorber plate temperature under climate condition in Khartoum, Kuala Lumpur and Edinburgh respectively. It can be observed that, the system different layers temperatures increases or decreases base on the variation in solar radiation and ambient temperature. Table 4 gives a summary of the maximum temperature at different layer of the new PVT system at the three locations.

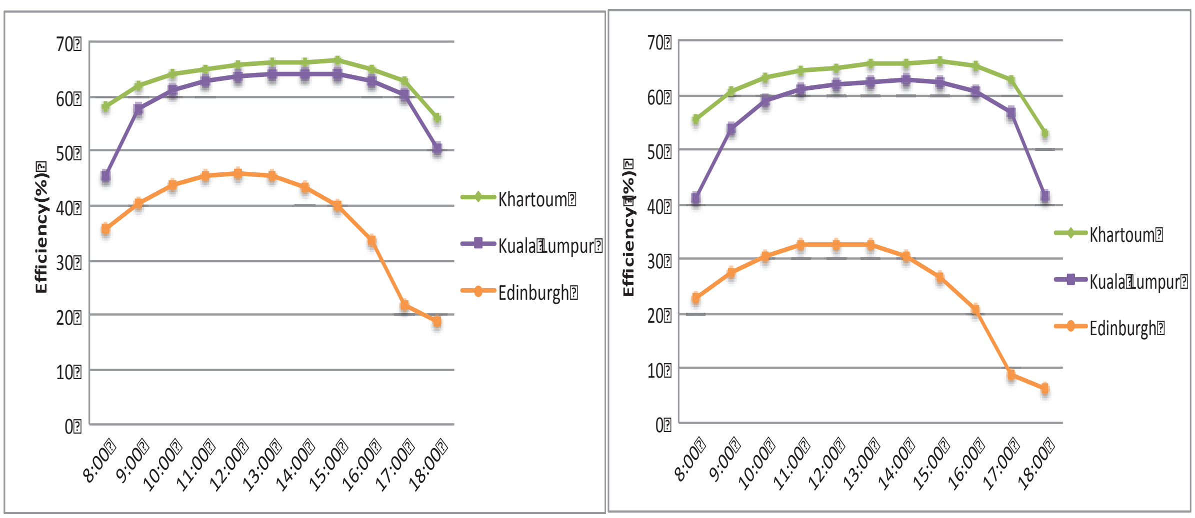
Table 4 Maximum temperature across the different layers of the new PVT

	Glass cover	PV1 (STPV1)	PV2 (STPV2)	Absorber plate
Khartoum	53.86ºC	57.41ºC	62.19ºC	67.54ºC
Kuala Lumpur	45.50ºC	49.69ºC	55.33ºC	61.74ºC
Edinburgh	18.58ºC	19.49ºC	20.72ºC	22.40ºC

Therefore, the above results indicate clearly that the system in Khartoum have the highest temperature followed by Kuala Lumpur. Edinburgh on the other hand shows low temperature compared to the other two locations. Different research was conducted and indicated that, PVT performance depends mainly on the absorber plate temperature, which is directly affected by solar radiation on the location (Fadhel, Sultan et al. 2013, Dupeyrat, Ménézo et al. 2014, Aste, Leonforte et al. 2015); hence, the above results is anticipated to have effect on the system performance.

3.2. Thermal efficiency of the new PVT

It is of important here to note that the new PVT is provided with two semi-transparent PV (i.e. STPV1 & STPV2 and glass cover. For the case of the PVT without glass cover, the STPV1 will act as the cover and transmit solar radiation to the STPV2. While for the case with glass cover, the STPV1 will act as the second cover and transmit the solar radiation to STPV2.



(a) (b)

Fig. 8 Thermal efficiency of new PVT with glass cover (a) and without glass covers (b).

Fig. 8 represent the thermal efficiency of the PVT system with glass cover (a) and without glass cover (b) at three different locations. It is clear that, there is continuous increase in thermal efficiency due to increase in solar radiation.

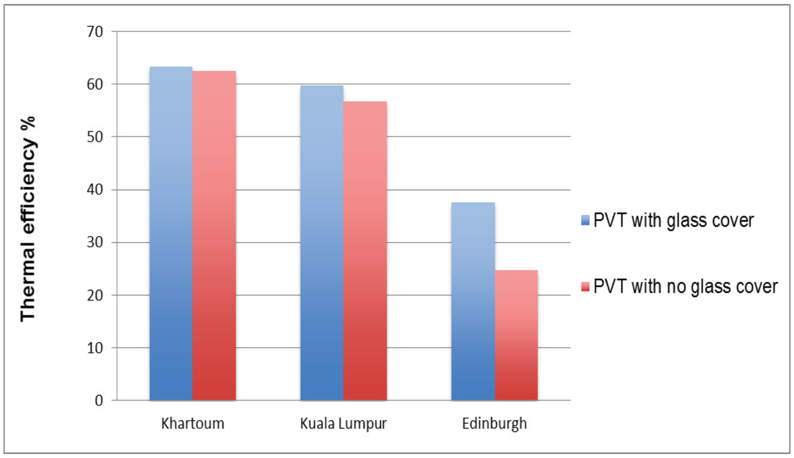


Fig. 9 comparison of averaged daily thermal efficiency at the three locations

Fig. demonstrates the average daily thermal performance of the new PVT system, it can be seen that, the PVT with glass cover indicates about 1% increase in thermal efficiency at Khartoum and about 4.1% increase in Kuala Lumpur. However, the PVT system with glass cover in Edinburgh account for nearly 10% increase in thermal efficiency. The new PVT without glass cover achieves high thermal efficiency at Khartoum, thus the PVT with glass cover have no significant improvement due to the higher ambient temperature. The PVT with glass cover in Kuala Lumpur gained slightly higher efficiency, hence achieving nearly the same result as Khartoum. However, the new PVT with glass cover in Edinburgh indicates significant increase in thermal efficiency. Previous research on glazed and unglazed PVT have proven that additional cover is more effective in PVT when applied to locations with low solar radiation and ambient temperature (KADHIM, YAZDI et al. 2013, Michael, Iniyan et al. 2015). This explains why there significantly increases of thermal efficiency in Edinburgh.

3.3. Electrical efficiency of the new PVT

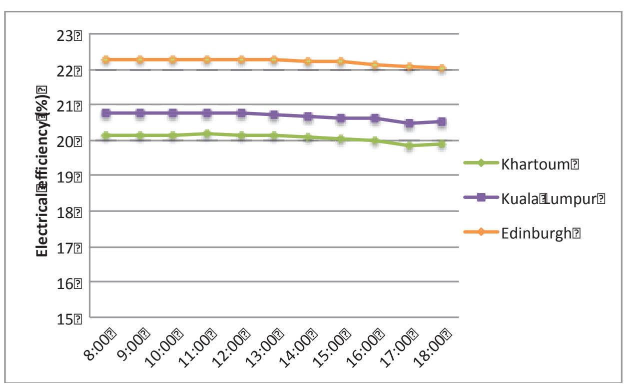


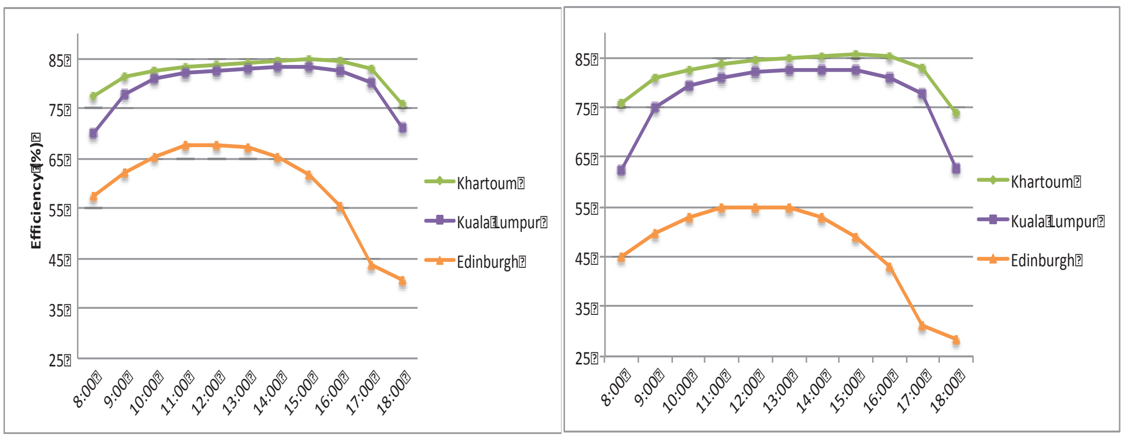
Fig. 2 Electrical efficiency of PVT in Khartoum, Kuala Lumpur and Edinburgh

Fig. 2 shows the Electrical efficiency of the new PVT system. It can be observed that, the system in Edinburgh achieves the highest electrical efficiency of 21.94%, followed by Kuala Lumpur with efficiency of 20.41% and Khartoum with efficiency of 19.54%. It has been illustrated in different research that the PV cell efficiency depends mainly on the cells temperature (Kumar and Rosen 2011, Aste, Leonforte et al. 2015). Hence, it is clear from the figure above that

Edinburgh has low ambient temperature compared to Kuala Lumpur and Khartoum. However, it is worthy to note that the actual performance (electrical energy output) depends maily on the solar radiation. This will be discussed in the later section of energy output. It has to be noted that the electrical efficiency above is a combination for SPTV1 and STPV2 elecerical efficiency which is about 13% and 7.5% respectively. STPV2 efficiecy is nearly half compared to STPV1, this is due to reduction of solar radiation reaching STPV2 as a result of absorption, reflection and transmissivity of solar radiation by STPV1.

34. Overall efficiency of new PVT system

Fig. shows the combined efficiency of the new PVT system. It illustrates the continuous increase in the combined PVT efficiency between 8:00 to 12:00 where the system receives maximum solar radiation. Similarly, there is a continuous decrease in efficiency toward evening hours of 18:00 due to decreasing solar radiation.



(a) (b)

Fig.11 the combined efficiency of the PVT with glass cover (a) and without glass cover (b)

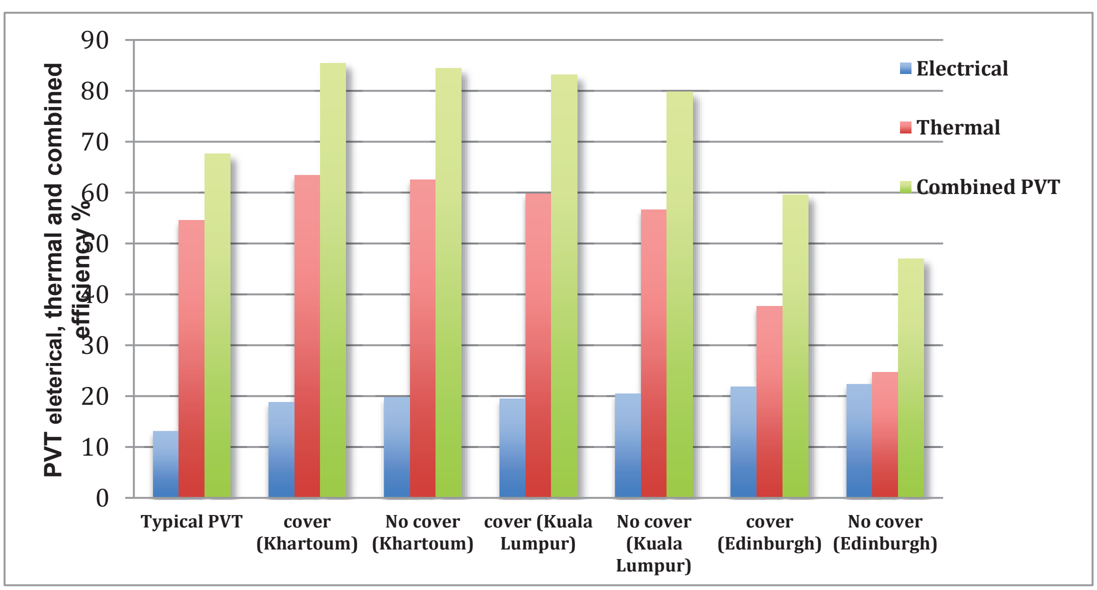


Fig. 3 Comparison of overall PVT efficiency in the three locations and conventional PVT in Kuala Lumpur

Fig. 32 shows comparison of the daily average of the electrical, thermal and combined efficiencies of the new PVT system compared to the conventional PVT (Fudholi, Sopian et al. 2014). It clear that, the PVT with glass cover in Khartoum experienced increases of the combined PVT efficiency by about 0.5%, while 4.1% in Kuala Lumpur and 11% Edinburgh. Previous research have demonstrated that the PVT efficiency depends on solar radiation and temperature (Chow 2010, Hasan and Sumathy 2010, Aste, Leonforte et al. 2015). It is also found that glazing is needed in low temperature location to improve the PVT efficiency (KADHIM, YAZDI et al. 2013, Kumar, Baredar et al. 2015). Amongst the three locations, Khartoum experience the highest temperature and solar radiation. Therefore, the PVT system already achieves nearly its maximum efficiency and hence the PVT with glass cover is leads to no further improvement. Similarly, Kuala Lumpur has relatively high temperature and solar radiation but lower than Khartoum, hence, the PVT with glass cover improves efficiency to nearly maximum, hence, making the system to achieve nearly the same efficiency as in Khartoum. Edinburgh on the other hand has lower solar radiation and ambient temperature hence low efficiency, but it can observed that, the PVT with glass cover increases combined efficiency by nearly 12% over PVT without glass cover. It can be seen that, the new PVT designed with twin transparent PV panels (either with glass cover or without glass cover) improve efficiency over the typical PVT system, hence achieving better performance. Finally, it can be noted that the results matches the trend of most previous studies on application of glazing to PVT system.

3.5. Energy output of the new PVT system

Figure 13 represents the useful thermal and electrical energy of the new PVT system respectively. It can be observed that, the thermal energy is significantly high in Khartoum and Kuala Lumpur and can reach 1.87MJ and 1.64MJ respectively (for a collector area of 0.762 m^2).

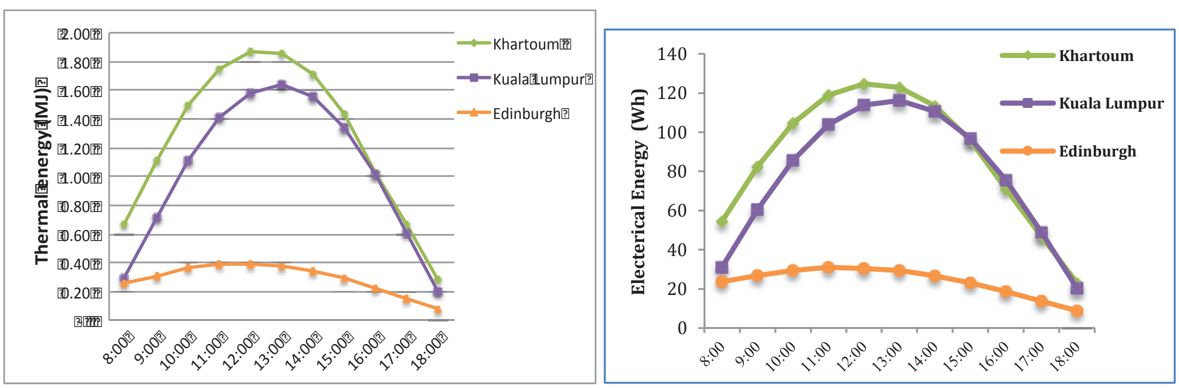


Fig. 4 Useful thermal and electrical energy of the new PVT system

The energy produced for the same collector area is relatively very low in Edinburgh with maximum output of 0.39MJ. Previously it has be illustrated that the energy output depend on the incoming solar radiation (Zondag 2008, Calise, d'Accadia et al. 2012, Tyagi, Kaushik et al. 2012). Hence the high performance in Khartoum and Kuala Lumpur due to relatively high solar radiation, the system performance in Edinburgh low due to low level of solar radiation.

Similarly, the electrical energy produce by the PVT system is significantly high in Khartoum and Kuala Lumpur with the system producing up to 125 Wh and 116 Wh respectively. The electrical energy produce by the system in Edinburgh is relatively low with maximum energy of 30Wh. However, it has to be noted that, the performance depends on solar radiation while efficiency depends on temperature. Therefore, although earlier results illustrated that the PVT electrical efficiency is higher in Edinburgh compared to Khartoum and Kuala Lumpur, the PVT achieves high performance (electrical energy output) in Khartoum and Kuala Lumpur due to high solar radiation compare to Edinburgh due to low solar radiation.

According to the results presented above and from previous research on PVT technology, it can be seen that the PVT is most effective in locations with high solar radiation and ambient temperature like Khartoum and Kuala Lumpur while for location similar to Edinburgh with low solar radiation and ambient, the PVT system can be considered not effective.

5. Conclusions

In this work, the performance of a new PVT system design with two semi-transparent PV panels was analysed under climate condition in Khartoum, Kuala Lumpur and Edinburgh with high, medium and low solar radiation and ambient temperature respectively. From the result presented, the following conclusion can be drawn.

- The performance of PVT system depends hugely on the solar radiation and ambient temperature, hence, the PVT have high performance in locations with high solar radiation and ambient temperature.
- The PVT with glass cover configuration yielded more efficiency than system without the cover, however, when comparing the performance in different locations. The glazing is ineffective in Khartoum, in Kuala Lumpur it leads to about 4% increase combined efficiency and in Edinburgh, the PVT with glazing increases the combined efficiency by about 12%. Therefore, it is proven that the glazing design is ineffective in locations with high ambient and might lead to significant improve in performance at location with relatively low solar radiation and ambient temperature.
- The combination of the two semi-transparent PV panels lead to significant increase in electrical efficiency from13% to 20.70% with about 12.7% for STPV1 and 7.8% for STPV2.
- Previous research illustrates that, a typical PVT has efficiency of 13% electrical, 60% thermal and 73% combined PVT (Hasan and Sumathy 2010). This analysis has illustrated that the new PVT configuration can achieve electrical, thermal and combined PVT efficiency of about 20.76%, 65.70% and 85.50% respectively. Therefore improving the PVT system efficiency by nearly 13.4%.
- Base on energy output of the PVT system, the PVT will yield significant result in climate conditions similar to Khartoum and Kuala Lumpur, but the system can be considered not suitable for climate condition similar to Edinburgh.

The increase efficiency leads to a remarkable achievement on PVT development and will make it suitable particularly in area with limited space. However, future studies will need to account for the economic analysis, as this development of twin PV panel and glass cover in a single PVT unit might lead to increase of production cost. Therefore the economic analysis will provide a better assessment as to whether the increase efficiency is economical feasible.

Conflict of Interest

The authors declare that they have no conflict of interest.

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